

Digital Twins for Smart Grid

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ABSTRACT

In today's world, no one can deny the fact that the power industry plays a crucial role in the progress of society. It can be seen as an engine driving the global economy forward and therefore directly influencing the day-to-day life of individuals. However, we are facing many important challenges in meeting the growing demand for energy with the limited resources. To deal with these challenges, there arises an urgent need for the modernization and strengthening of our power grids. The smart grid has emerged as an advanced energy infrastructure that enhances the capabilities of previous grids, making them faster, more intuitive, and collaborative. Digital twin technology has emerged as a transformative development in smart grids, offering extensive benefits from asset management to predictive maintenance. It represents a transformative approach for monitoring and regulating smart grids. The digital twin keeps a synchronized virtual replica of each asset and of the grid as a whole. The convergence of smart grids and digital twin signals progresses, offering a roadmap for sustainable and efficient energy systems in the future. This integration will help tackle the contemporary challenges related to energy management. This paper provides an overview of the applications of digital twin technology in modern smart grids.

KEYWORDS: digitalization, digital twin, smart grid, energy, power systems.

INTRODUCTION

The global energy landscape is undergoing a rapid and profound transformation. The integration of renewable energy sources, distributed energy resources, and electric vehicles necessitates a paradigm shift in grid management. Digital twin (DT) technology has emerged as a transformative solution, offering a high-fidelity, real-time virtual representation of physical grid assets. By bridging the physical and digital realms, DTs facilitate predictive maintenance, optimize energy storage, enhance cybersecurity, and support the seamless integration of renewable energy, thereby paving the way for resilient and efficient modern power systems. Figure 1 shows a typical digital twin [1]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the energy sector. Figure 2 shows the conceptual model of a digital twin [2].

The electrical power sector is currently facing significant challenges, including ecological consciousness, the need for clean and sustainable energy management, insufficient energy distribution networks, and increasing energy demands. To address these challenges, the concept of the "smart grid" has evolved, characterized by bidirectional flows of both electricity and information. In the context of smart grids, DTs serve as the "central nervous system," enabling operators to monitor, simulate, predict, and optimize grid performance with unprecedented accuracy. The deployment of digital twins in smart grids spans various operational and strategic domains, offering significant improvements in efficiency and reliability [3].

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model

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underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion. Figure 4 depicts the digital twin conceptual architecture [6], while Figure 5 shows DT enabling technology [7].

There are numerous requirements to describe “digital twin.” To be considered a digital twin, the model must have some specific characteristics such as [8]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.

Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.

2. Scalability (ability to analyze different scales of information);
3. Interoperability (ability to convert, match and establish equivalence between representation models);
4. Expansibility (ability to integrate models);
5. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
6. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins.

WHAT IS SMART GRID?

The term “grid” traditionally refers to the electric grid, a network comprising of electricity generation, electricity transmission, electricity distribution, and electricity control. It delivers electricity from the power plant to a residential or commercial building. An example of the traditional or conventional electric grid is shown in Figure 6 [9]. A “smart grid” is an enhancement of the traditional (dumb) electric power grid. It is also known as “intelligent grid,” or “The Grid 2.0.” It is the modernization of the power delivery system. It is a transformation of the legacy unidirectional electric grid into automatic intelligent system of bidirectional exchange of electric power and information. A smart grid may be defined as any combination of enabling technologies, hardware, software, or practices that collectively make the delivery infrastructure (or the grid) more reliable, more versatile, more secure, more accommodating, more resilient, and ultimately more useful to consumers [10]. A smart grid basically consists of overlaying the physical power system with the information system. It transforms the way power is delivered, consumed, and managed. It is one of the critical applications of the IoT system. Figure 7 shows a typical smart grid [11].

From an architectural point of view, the smart grid is comprised of three layers: (1) the physical power layer (transmission and distribution), (2) the data transport and control layer (communications and control), and (3) the applications layer (applications and services). From technology viewpoint, smart grid technologies are divided roughly into three groups:

well-established, advanced, and emerging. From the technical perspective, the smart grid can be divided into three major systems [12]:

- *Smart infrastructure system:* This is the energy, information, and communication infrastructure underlying the smart grid. This allows two-way flow of electricity and information. This implies that the users may put back electricity into the grid. The system enables multiple entities (such as intelligent devices, dedicated software, control center, etc.) to interact.
- *Smart management system:* This provides advanced management and control services. Efficient management is fundamental for efficient operation of smart grids. Management of smart grid includes the development and implementation of smart metering, real time pricing, efficient management of renewable energy sources, and management of transmission and distribution networks.
- *Smart protection system:* This provides advanced reliability analysis, fault protection, and security services. The existing infrastructure has become vulnerable to several security threats.

Smart grids are interconnected with these major systems. In other words, it connects electric generation systems, electric transmission systems, electric distribution systems, customer information and management systems, usage and meter management systems, and billing systems. Figure 8 shows the evolution of electric grid [13].

DIGITAL TWIN IN SMART GRID

The electrical power sector is currently undergoing the most radical transformation in its history, which dates back to the deployment of the first power grid nearly 150 years ago. A convergence of forces - including the rapid growth of distributed energy resources (DERs), the rise of electric vehicles, aging infrastructure, and the urgent need to meet net-zero climate targets - is stretching conventional power grids to their functional limits. Traditional power grids, which rely on centralized, static infrastructure, are struggling to accommodate the integration of distributed energy resources (DERs) such as solar and wind power, which introduce intermittency and variability. To address these issues, the concept of the smart grid has been developed, emphasizing bidirectional communication and advanced control systems. Traditional grid management approaches, which rely on static models and legacy supervisory control and data acquisition (SCADA) systems, are increasingly inadequate for managing the complexity and dynamism of modern energy networks [3].

Digital twin technology has emerged as a cornerstone of next-generation smart grid management and as one of the most promising innovations in the energy sector. A digital twin may be regarded as a real-time, high-fidelity virtual representation of a physical asset or system. In the energy sector, an electric digital twin grid acts as a virtual mirror of the physical infrastructure, enabling real-time monitoring, simulation, and intelligent decision-making. Today, DT has matured into a sophisticated platform underpinned by the Internet of things (IoT), artificial intelligence (AI), big data analytics, and cloud computing. A DT of an electrical network functions as a virtual replica of numerous subsystems and individual components within the system. DTs enable virtual modelling for optimizing operations, predictive maintenance, and real-time monitoring. In renewables, they support wind farms and solar PV by improving performance analysis, fault detection, and grid integration. Investment in DT technology within the energy sector, particularly in renewables, has surged due to its ability to enhance reliability, efficiency, and sustainability [14]. Figure 9 shows a typical DT of a power grid [15].

APPLICATIONS OF DIGITAL TWIN IN SMART GRID

The application of DT technology in smart grid asset management encompasses three critical aspects: strategic maintenance planning, lifecycle management, and performance optimization. Common applications of DT in smart grid include the following [3,16]:

- *Real-Time Monitoring:* One of the foundational applications of digital twins in smart grids is the real-time monitoring of grid assets and operations. By continuously ingesting data from IoT sensors, smart meters, and SCADA systems, the digital twin maintains an accurate reflection of the physical grid's current state. This allows operators to visualize power flows, voltage levels, and equipment status across the entire network, from generation down to the distribution level. Digital twins enable real-time health monitoring and performance analysis of grid components. By leveraging sensor data and advanced analytics, they can provide instant feedback on the condition of electrical assets, detect anomalies, and assess performance degradation over time.
- *Integration of Renewable Energy:* The intermittency of wind and solar energy poses significant stability challenges. The incorporation of renewable energy sources into the grid is essential for sustainable development but introduces variability and unpredictability in the

power supply. Digital twins assist in the seamless integration of these energy sources by simulating their impact on the grid, allowing operators to anticipate fluctuations and adjust the system accordingly. This capability ensures a stable energy supply and optimizes clean energy utilization, by reducing dependence on non-renewable resources and decreasing carbon emissions.

- *Cybersecurity:* The increasing digitalization of smart grids, while enabling the operational benefits described above, simultaneously expands the attack surface for malicious actors. As smart grids become increasingly connected, their vulnerability to cyberattacks grows. Digital twins enhance cyber-resilience by establishing a baseline of normal operational behavior - any deviation, whether caused by a physical fault or a malicious intrusion, can be rapidly identified. Advanced frameworks integrate DTs with machine learning classifiers to improve detection and classification of cyberattacks, enabling automated, self-healing grid responses. Digital twins can monitor grid operations in real time to detect anomalies that may indicate a cyber intrusion, flagging them for further investigation.
- *Load Balancing:* Digital twin technology plays a crucial role in load balancing and optimization in smart grids. By creating a dynamic digital replica of the physical grid, operators can simulate various load scenarios in real time, allowing for the prediction and mitigation of potential imbalances before they occur. This proactive approach not only ensures a stable and efficient distribution of electrical power but also optimizes the grid's operational efficiency.
- *Demand Response:* Demand response management is a critical component of modern smart grids, aimed at adjusting the demand for power instead of the supply. Digital twins facilitate a more responsive and flexible demand management system by accurately modeling the grid and consumer behavior. This allows utilities to incentivize reduced consumption during peak times and manage the distribution of resources more effectively. The integration of digital twins in demand response programs enhances the grid's ability to adapt to real-time changes and maintain an equilibrium between supply and demand, contributing to overall energy savings and system.
- *Asset Management:* The management of physical grid assets - including transformers, switchgear, cables, and wind turbines - represents a major operational and financial challenge for utilities.

Historically, maintenance strategies were either purely reactive, addressing failures after they occurred, or calendar-based, performing scheduled inspections regardless of actual asset condition. Both approaches are inefficient: reactive maintenance leads to unplanned outages and emergency repair costs, while calendar-based maintenance wastes resources on assets that remain in good health. Digital twins enable a fundamentally superior approach: condition-based predictive maintenance. By continuously ingesting sensor data from physical assets, the digital twin monitors equipment health in real time, applying AI and machine learning algorithms to identify degradation patterns and predict failures before they manifest.

- *Regulatory Compliance:* There is a critical need for a new regulatory framework of this new emerging technology. The energy sector is among the most heavily regulated industries in any economy, and the rapid pace of digitalization has outstripped the evolution of the policy and standards frameworks that govern it. Digital twins improve regulatory compliance and reporting, streamlining the documentation of security controls and audit trails required by standards such as NERC CIP in North America and the NIS2 Directive in Europe. By automating these processes, digital twins reduce the administrative burden on security teams and enable a more consistent, auditable approach to grid security governance.

BENEFITS

The benefits of digital twins in smart grids include real-time operational visibility, renewable energy integration, predictive asset maintenance, enhanced cybersecurity, and long-term grid planning. One of the most significant and immediately impactful benefits of digital twins in smart grids is the provision of comprehensive real-time operational visibility. Digital twin technology holds immense promise for revolutionizing the management, optimization, and resilience of smart grids, serving as a critical catalyst for the global energy transition. Other benefits of DT in smart grid include the following [3,16]:

- *Automation:* Digital twins support the automation of routine planning tasks, such as the verification of grid connection requests for photovoltaic systems and heat pumps. As the volume of such requests grows exponentially, automated digital twin-based processing reduces costs and eases the burden on grid operators, enabling them to manage increasing complexity without proportional increases in staffing.

- **Grid Planning:** Digital twins confer substantial advantages in the domain of long-term grid planning and capital investment. They provide a risk-free virtual environment for grid planning. Operators can simulate extreme weather events, cyberattacks, or sudden EV charging load surges to evaluate grid resilience and defer capital-intensive infrastructure investments. Planners can model the impact of different feed-in and consumption scenarios on grid stability, identify bottlenecks, and assess the return on investment of alternative infrastructure configurations before committing capital.
- **Monitoring Assets:** A traditional approach to transformer monitoring might involve periodic manual inspections, missing early fault indicators, whereas a DT model uses real-time voltage and current data to detect issues instantly, reducing failure risks. The evolution of power grid is driven by the increasing complexity of energy systems, the integration of renewable energy sources, the rise of electric vehicles, and the growing demand for real-time monitoring and control.
- **Predictive Maintenance:** Traditionally, maintenance in power grids has been either reactive (fixing equipment after it fails) or scheduled (performing maintenance at fixed intervals regardless of condition). Digital twins shift maintenance from reactive to proactive. By continuously monitoring the health of critical assets like transformers and wind turbines through sensor data and AI analytics, DTs detect subtle anomalies indicative of impending failure. This extends asset lifespans, reduces repair costs, and minimizes service interruptions. DTs are actively used to model predictive maintenance in large-scale power transformers, combining real-time data with AI-driven analytics. By continuously monitoring asset health data - such as temperature, vibration, and load history - and applying machine learning algorithms, digital twins can predict equipment failures before they happen.
- **Efficiency:** The synthesis of digital twin (DT) technology into smart grid systems has emerged as a promising approach for enhancing operational efficiency, reliability, and resilience in energy management. DTs offer a virtual representation of physical assets and processes, enabling real-time monitoring, predictive analytics, optimization, and control.

CHALLENGES

In spite of the profound benefits, the widespread adoption of digital twins in smart grids faces several significant challenges. These include the massive volume of data that must be securely transmitted, stored, and processed in real time; interoperability issues between legacy grid systems and new IoT devices; and the high initial investment costs, which can be prohibitive for smaller utility companies. Other challenges of DT in smart grid include the following [3,16]:

- **High Costs:** Developing and deploying a comprehensive DT for a smart grid requires substantial upfront capital investment. For large national transmission operators, these investments may run into hundreds of millions of dollars. For smaller operators, the financial barrier is even more acute. Justifying this level of investment requires a clear and credible business case, with demonstrable returns in the form of reduced operational costs, deferred capital expenditure on physical infrastructure, improved grid reliability, or new revenue streams from flexibility services. Demonstrating return on investment (ROI) for DT implementations can be difficult, especially for energy storage systems, where high costs may not be justified in all scenarios.
- **Technical Challenges:** The foundational challenge of building a digital twin for a smart grid lies in the sheer scale and complexity of the physical system it must mirror. A modern power grid is a vast cyber-physical system comprising millions of interconnected components—generators, transmission lines, substations, distribution feeders, smart meters, and increasingly, distributed energy resources at the grid edge. Constructing a virtual replica of such a system that is simultaneously accurate, real-time, and computationally tractable is an engineering challenge of the highest order.
- **Computational Complexity:** A digital twin must maintain high model fidelity. In inverter-dominated renewable grids, the DT must account for complex alternating current (AC) power-flow physics, network thermal limits, voltage stability bounds, protection coordination, and multi-timescale operations ranging from sub-second frequency responses to hourly and daily scheduling. Achieving this level of detail requires computationally intensive electromagnetic transient (EMT) and phasor-domain simulations. The tension between model accuracy and computational speed is acute: a highly detailed physics-based model may be too slow for real-

time control, while a simplified model may be insufficiently accurate for reliable decision-making.

- *Data Privacy:* The bidirectional flow of data in smart grids means that DTs routinely process sensitive consumer data, including real-time electricity usage patterns that can reveal detailed behavioral habits, occupancy patterns, and lifestyle information. Strict data privacy regulations—most notably the General Data Protection Regulation (GDPR) in Europe—impose significant constraints on the collection, storage, and sharing of this data. Compliance with these regulations adds legal complexity to DT design.
- *Data Quality:* A digital twin is only as effective as the data that feeds it. The reliance on massive, continuous volumes of real-time data from heterogeneous sources—IoT sensors, smart meters, weather stations, market signals, and SCADA systems—introduces severe data management and security vulnerabilities that must be addressed with equal rigor as the technical modeling challenges. For a DT to accurately reflect the physical grid, it requires a continuous, high-quality data stream from thousands or millions of endpoints. Missing, corrupted, delayed, or inconsistent data can lead to inaccurate state estimation, flawed control decisions, and ultimately, grid instability. The sheer volume of data generated by a grid-scale DT is immense. Storing, processing, and analyzing this data in real time requires sophisticated data architectures.
- *Data Governance:* Data governance is necessary to determine who will be responsible for data at every stage of their lifecycle, including creation, initial storage, use, and maintenance, withdrawal from storage, and final deposition. It includes information about access control, data consent and policies, data quality, compliance, and audits. A lack of clarity on the access to the data can lead to potential security issues or undermine the usefulness of the data. Data provenance helps determine the original source of data and the changes that have occurred over time.
- *Scalability:* A major challenge is scalability. A digital twin that accurately models a single substation or microgrid may not scale gracefully to represent an entire regional or national grid. As the number of modeled components grows, the computational resources required for real-time simulation grow non-linearly, creating bottlenecks in processing and data storage.
- *Integration:* Perhaps the most immediate and pervasive technological challenge is the integration of DT technologies with the existing, aging grid infrastructure. A significant portion of power grid assets in developed nations dates back to the early-to-mid 20th century and was not designed with digitalization in mind. Integrating cutting-edge DT platforms with legacy Supervisory Control and Data Acquisition (SCADA) systems, outdated communication protocols, and aging hardware presents a formidable technical bottleneck. Figure 10 shows key aspects of integration [16].
- *Security:* A system of sensors, displays, campaigns, processes for data collecting and processing, and other components make up the smart grid and are all vulnerable to cyberattacks. Cybersecurity itself represents a paradox: while digital twins enhance grid security, they also store and process large quantities of sensitive operational data, making them potential targets for cyberattacks. Ensuring the security of the digital twin itself - through robust data encryption, access controls, and anomaly detection - is therefore a prerequisite for realizing its security benefits.
- *Interoperability:* Interoperability presents another significant challenge. For each component in the DT to communicate effectively with its physical counterpart, seamless interoperability is essential. Smart grids are heterogeneous ecosystems comprising equipment and software from a multitude of vendors, each adhering to different proprietary protocols and data formats. Digital twins must integrate with existing SCADA and geographic information system (GIS) infrastructure, and must comply with a complex landscape of standards. For smaller grid operators, the technical and financial demands of digital twin deployment can quickly exceed their resources and expertise, underscoring the need for standardized, scalable solutions and supportive regulatory frameworks.
- *Skills Gap:* The operation and maintenance of AI-driven digital twins demand a highly specialized, interdisciplinary workforce that is proficient in data science, machine learning, cybersecurity, software engineering, and power systems engineering. This combination of skills is rare and in high demand across multiple industries simultaneously. The energy sector currently faces a significant human capital shortage in these digital competencies.

Figure 11 shows the next generation of electric grid challenges [13].

FUTURE OF DIGITAL TWINS IN SMART GRID

The electrical power sector is currently experiencing the most radical shift since its inception over a century ago. As the energy sector continues its transition toward a decentralized, renewable-heavy future, the adoption of digital twins will be instrumental in ensuring that power grids remain reliable, efficient, and resilient. Looking ahead, the evolution of digital twins will be characterized by deeper integration with emerging technologies, driving the smart grid toward greater autonomy and resilience. The convergence of digital twins with artificial intelligence, IoT, and blockchain technologies promises to further unlock the potential of smart grids, paving the way for a sustainable and secure energy future. The convergence of AI and digital twins also enables a new paradigm of autonomous grid management. Future systems will likely feature conversational interfaces where grid operators can query the digital twin in natural language. The ultimate trajectory of digital twin technology in the energy sector is the realization of the autonomous, self-healing grid [3]. The future of DT technology in power grids is promising, with significant advancements expected in both research and practical deployment.

CONCLUSION

Digital twin technology represents a cornerstone in the modernization of electrical power systems. It represents a paradigm shift in the management, operation, and planning of smart grids. It is not merely a technological enhancement but a fundamental enabler of the intelligent, resilient, and sustainable power grid of the future. By providing a dynamic, intelligent, and predictive bridge between the physical grid and its virtual counterpart, DTs empower operators to navigate the complexities of the energy transition.

The use of digital twin in the energy sector is growing exponentially, driven by the need for sustainability, efficiency, and resilience. Digital twins are evolving, yielding new technological and scientific breakthroughs that direct development towards more seamless and autonomous solutions. They provide a significant opportunity to push the management and optimization of smart grids forward. As this technology matures, we anticipate more widespread adoption, leading to more resilient, adaptive, and intelligent power grid systems. More information about digital twin in smart grid can be found in the books in [17,18].

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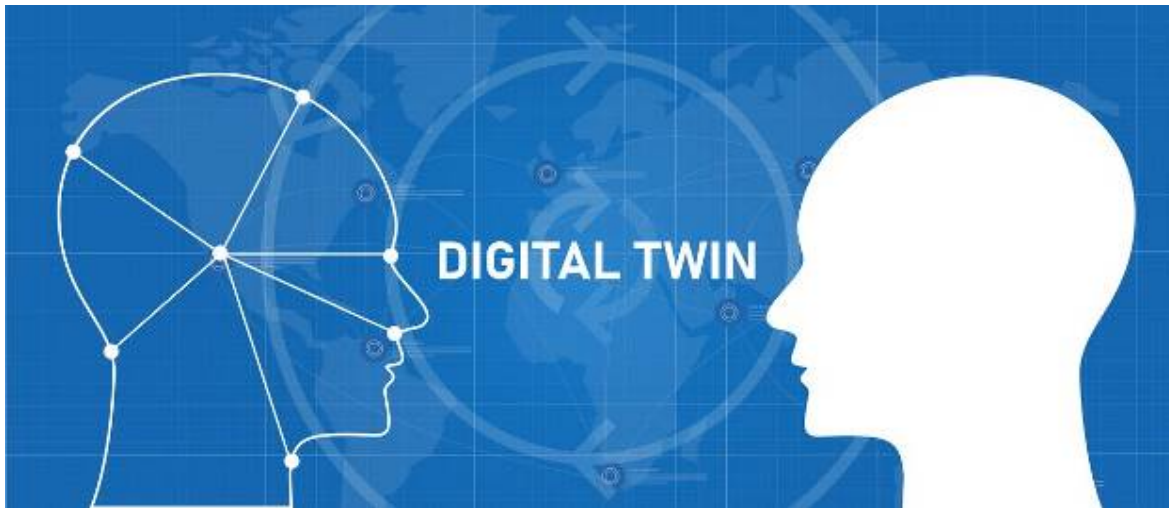


Figure 1 A typical digital twin [1].

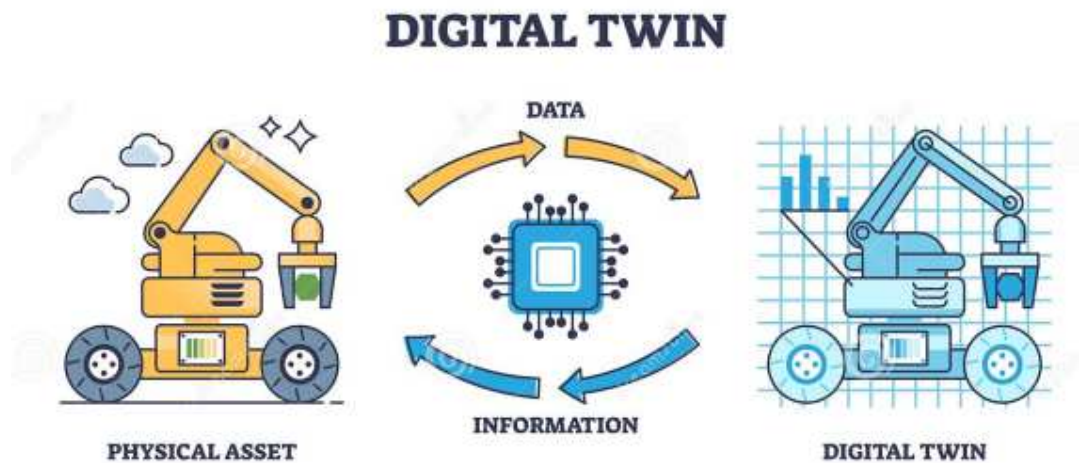


Figure 2 Conceptual model of a digital twin [2].

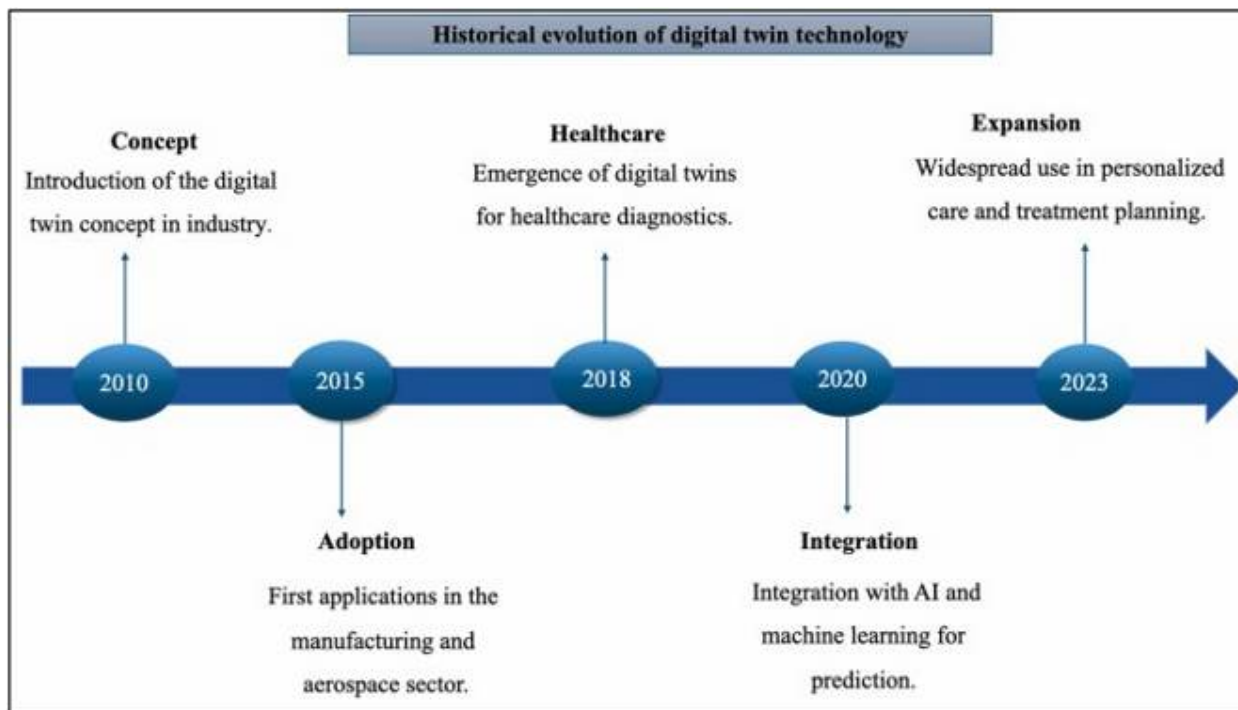


Figure 3 The historical evolution of DT technology [5].

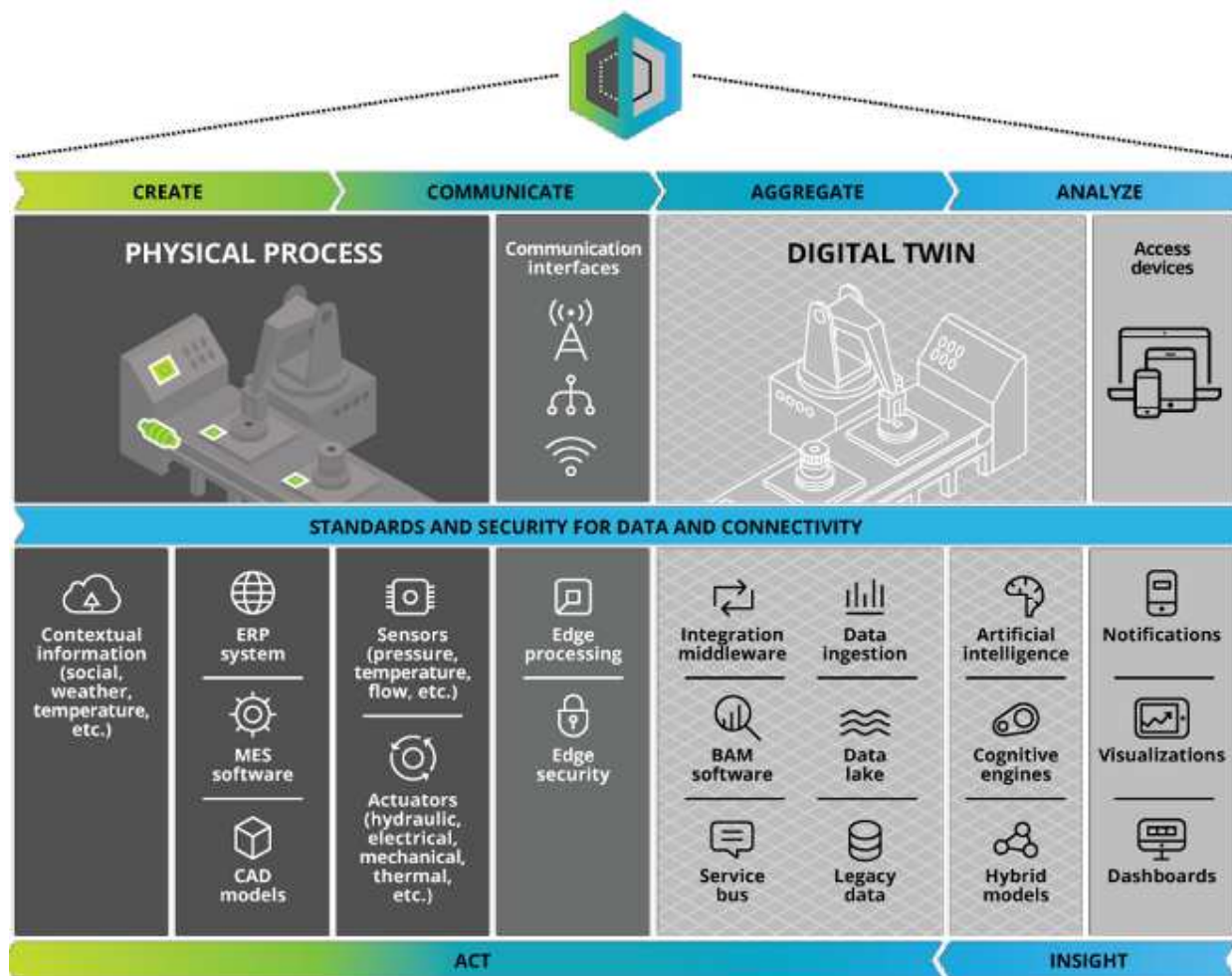


Figure 4 The digital twin conceptual architecture [6].

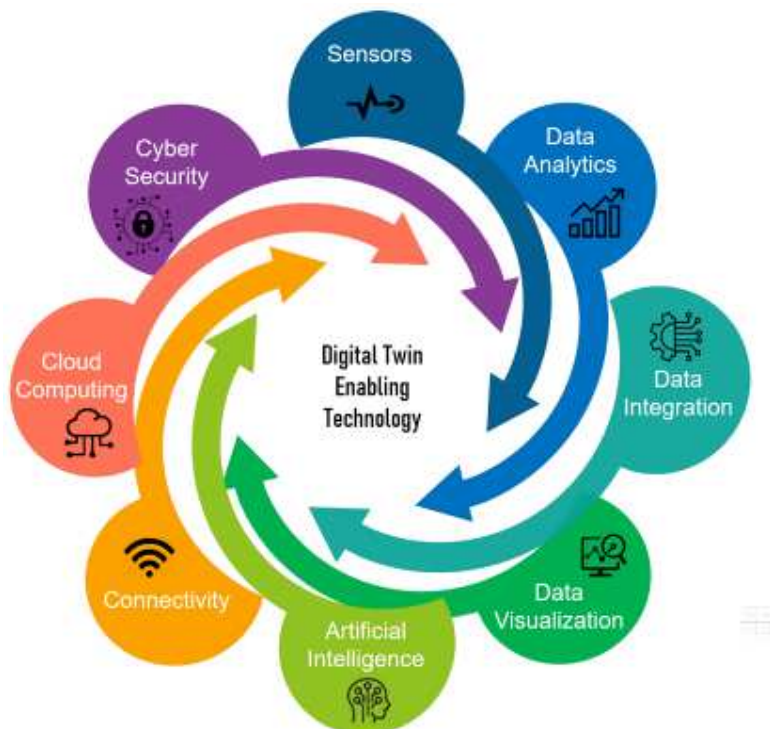


Figure 5 DT enabling technology [7].

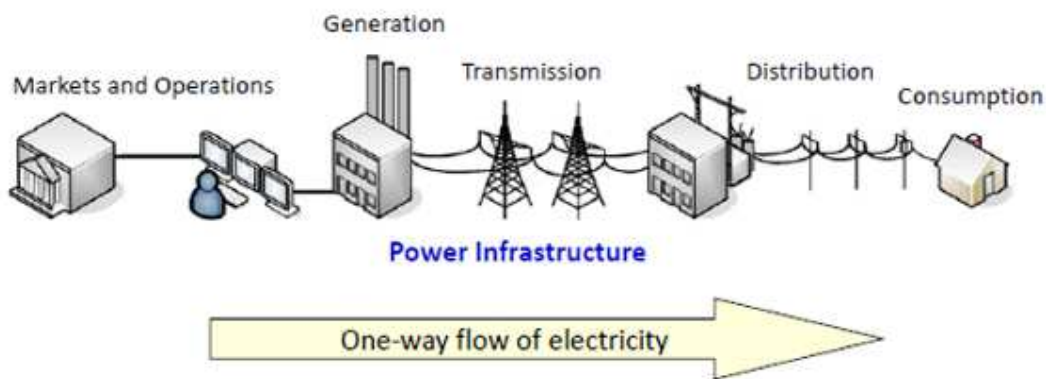


Figure 6 A typical traditional power grid [9].

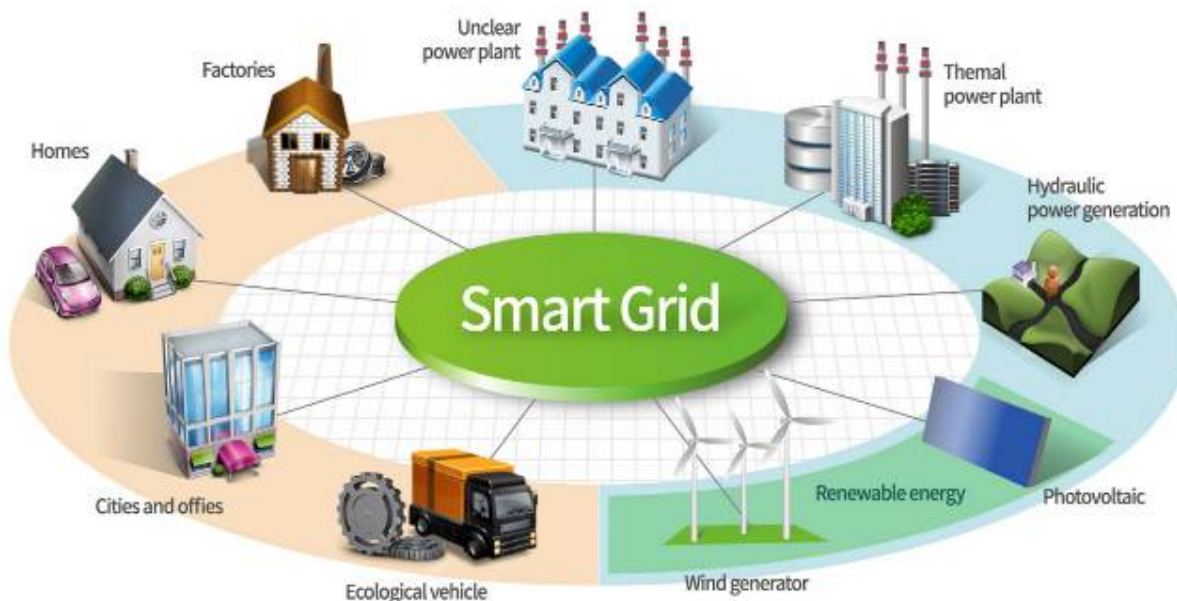


Figure 7 A typical smart grid [11].

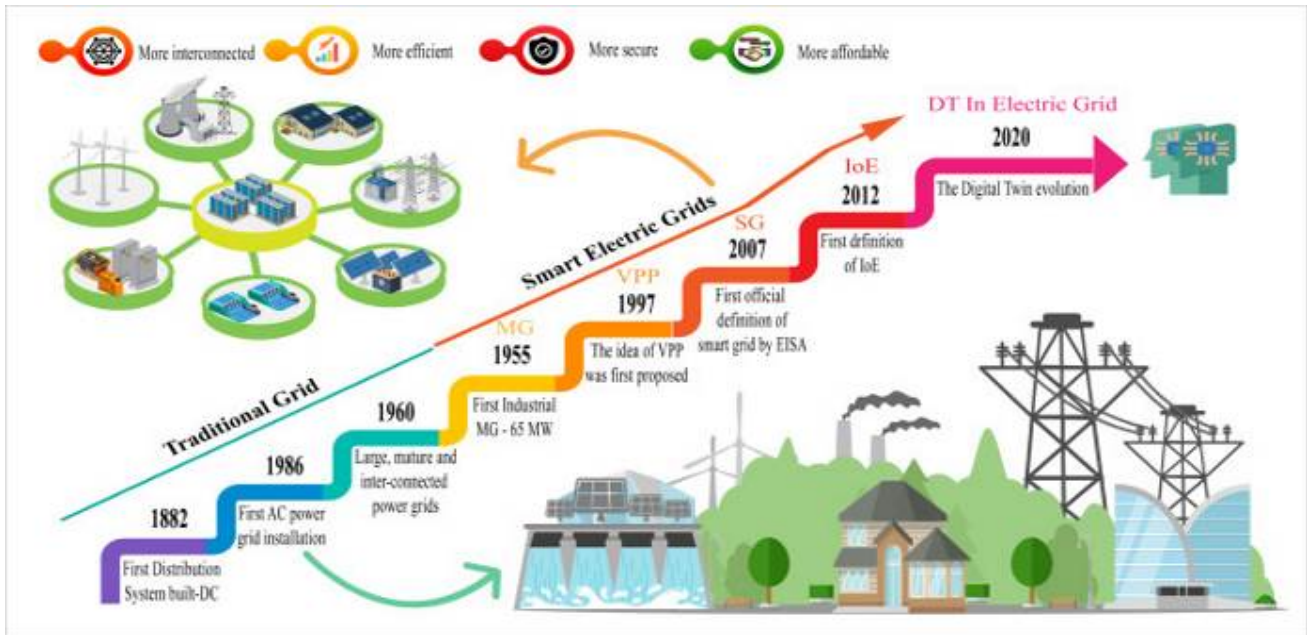


Figure 8 Evolution electric grid [13].

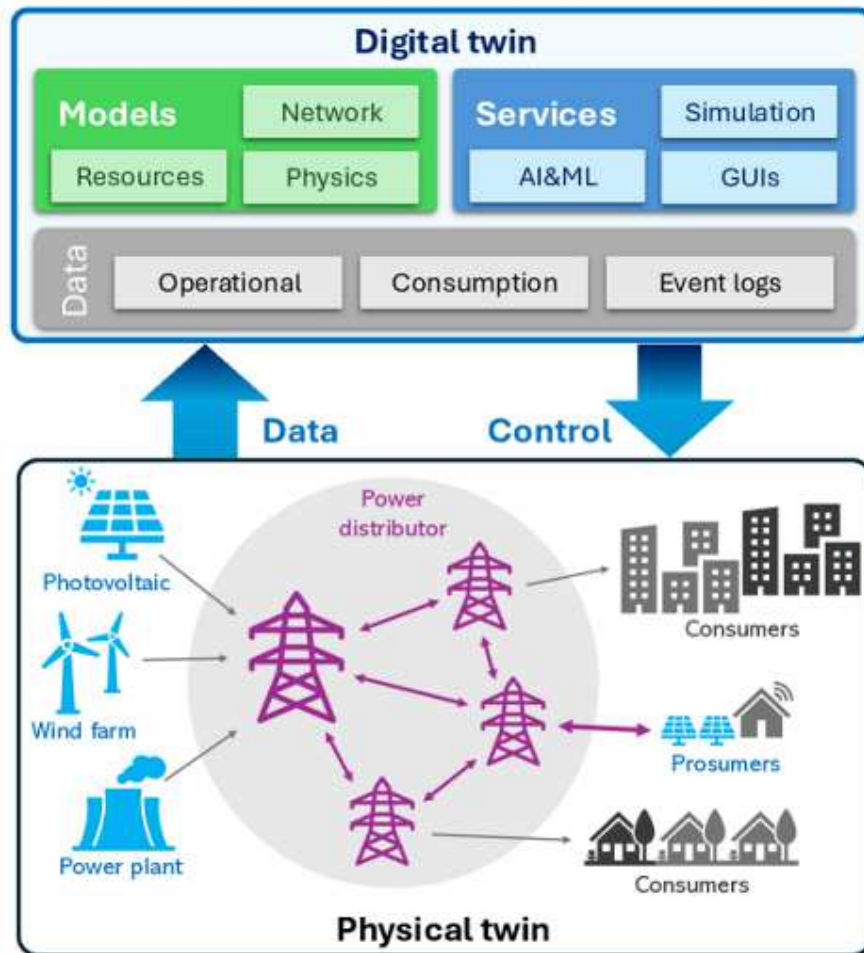


Figure 9 A typical DT of a power grid [15].

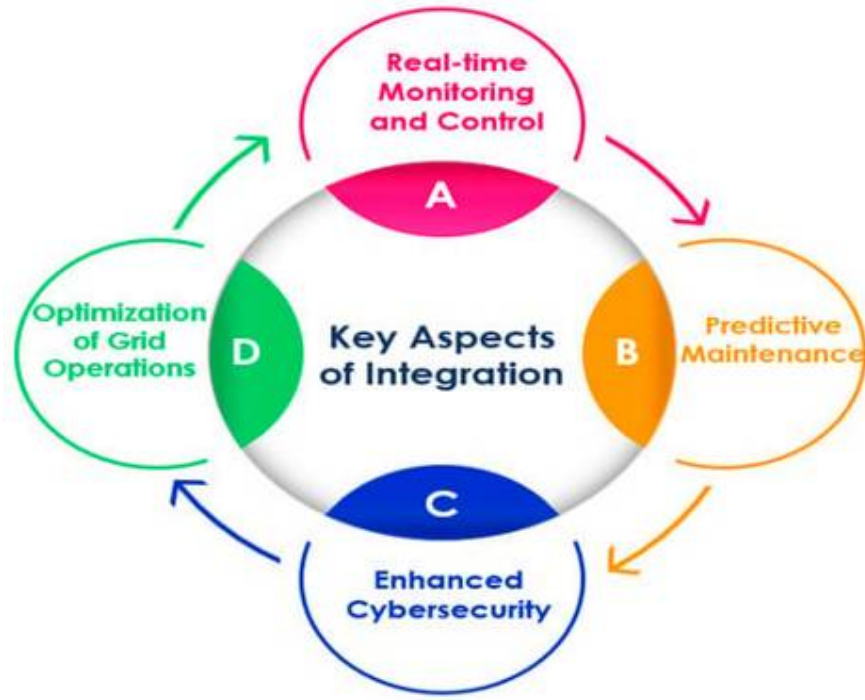


Figure 10 Key aspects of integration [16].

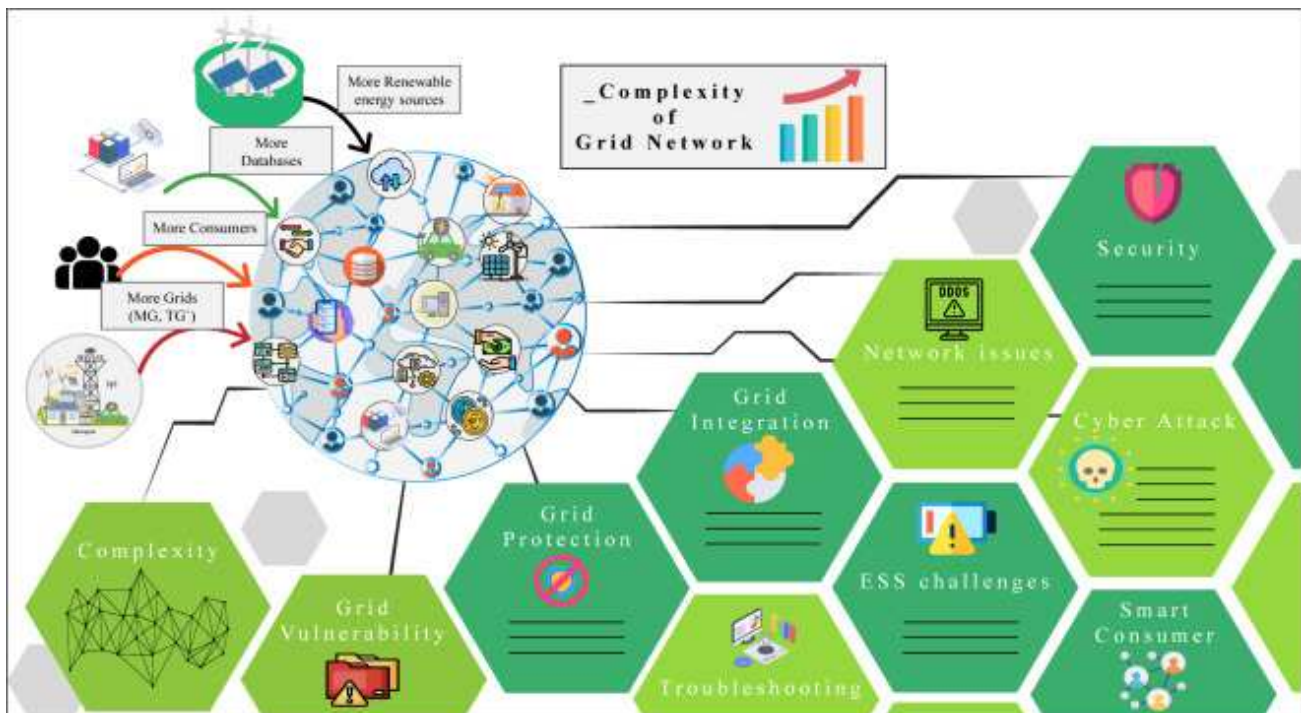


Figure 11 Next generation of electric grid challenges [13].